



Flight Deck Motion System (FDMS): Operating Concepts and System Description

J.L. Colwell

Defence R&D Canada

Technical Memorandum

DRDC Atlantic TM 2004-003

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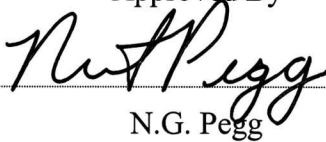
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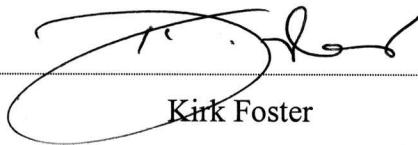
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Abstract

The Flight Deck Motion System (FDMS) is an active operator guidance system for assisting the shipboard Landing Safety Officer (LSO) when landing helicopters in high seas. New concepts for identifying and tracking 'quiescent periods' in real time are described, and the FDMS capability and reliability are described. Three operating modes are discussed: a quiescent period indicator for real time guidance, a flight planning mode to assist in decision making, and a flight deck data recorder. The measurement and calculation of ship motion parameters is discussed, and the definition of real time criteria is described.

Résumé

Le système d'aide à l'appontage (FDMS) est un système de guidage à opérateur actif destiné à aider l'officier de sécurité d'appontage lorsqu'il s'occupe de l'appontage d'hélicoptères par mer agitée. On décrit de nouveaux concepts visant à cerner et à suivre les « périodes de repos » en temps réel : un indicateur de périodes de repos pour guidage en temps réel, un mode de planification de vol pour aider à la prise de décision et un enregistreur de données sur le pont d'envol. La mesure et le calcul des paramètres de mouvement du navire sont abordés, et la définition de critères en temps réel est présentée.

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Executive Summary

Introduction

The Flight Deck Motion System (FDMS) is an active operator guidance system for assisting the shipboard Landing Safety Officer (LSO) when landing helicopters in high seas. With existing systems and procedures, the helicopter pilot and LSO are consistently successful at identifying when ship roll motions are ‘within limits’ for a safe landing, but cannot reliably identify when ship vertical motions are within limits. The primary function for the FDMS is to provide a ‘Quiescent Period Indicator’ (QPI), which identifies when ship motions are within limits and when they are not.

Results

This report documents the FDMS operating concepts and system parameters in sufficient detail for establishing engineering specifications. Important new concepts are discussed, including how to quantify quiescent periods in real time, and what system capabilities are realistic for warning operators on operational limits with respect to current ship motions. System component locations are described, and operating modes are summarized. The acquisition and calculation of required ship motion parameters are discussed, and procedures for defining suitable motion criteria are described.

Significance

The primary reason for advocating development of the FDMS is to increase operational safety and efficiency, but it will also provide solutions for a number of existing problems on CF ships. The FDMS will remove current artificial constraints on the City Class ship motion “operational envelope” for helicopter landings, and it will resolve “unsatisfactory deficiencies” identified during flight deck certification trials on all three air-capable CF ship classes.

Future Plans

Options for future work are discussed, including: operational tests and validation; applications to other helicopter operations and general shipboard activities; and, possible enhancements for increasing system capabilities.

Colwell, J.L. 2004. Flight Deck Motion System (FDMS): Operating Concepts and System Description. TM 2004-003. DRDC Atlantic.

Sommaire

Introduction

Le système d'aide à l'appontage (FDMS) est un système de guidage à opérateur actif destiné à aider l'officier de sécurité d'appontage lorsqu'il s'occupe de l'appontage d'hélicoptères par mer agitée. Grâce aux procédures et aux systèmes actuels, le pilote de l'hélicoptère et l'officier de sécurité d'appontage réussissent à tout coup à savoir quand les mouvements en roulis du navire se trouvent « dans les limites » d'un appontage sûr, mais ils ne peuvent savoir avec certitude quand les mouvements verticaux (pilonnement) du navire se trouvent dans les limites. La principale fonction du FDMS consiste à fournir un indicateur de périodes de repos, lequel signale quand les mouvements du navire se trouvent dans les limites et quand ils ne le sont pas.

Résultats

Le présent rapport documente les concepts d'exploitation du FDMS et les paramètres du système suffisamment en détail pour permettre d'établir des spécifications techniques. D'importants nouveaux concepts y sont traités, notamment comment quantifier les périodes de repos en temps réel et quelles capacités du système sont réalistes pour avertir les opérateurs des limites opérationnelles par rapport aux mouvements actuels du navire. L'emplacement des composants du système est décrit, et les modes d'utilisation sont résumés. L'acquisition et le calcul des paramètres de mouvement requis du navire sont abordés, et des procédures visant à définir des critères de mouvement appropriés sont présentés.

Portée

La principale raison de préconiser la mise au point du FDMS réside dans l'amélioration de la sécurité opérationnelle et de l'efficacité. Mais ce système offrira aussi des solutions à un certain nombre de problèmes qui affligent les navires des FC. Le FDMS éliminera les contraintes artificielles qui minent actuellement le « domaine opérationnel » des mouvements des navires de la classe City pour ce qui est des appontages d'hélicoptère, et il permettra de régler « les lacunes insatisfaisantes » relevées lors des essais de certification des ponts d'envol des trois classes de navire des FC pouvant recevoir des aéronefs.

Recherches futures

Diverses avenues pour les recherches futures sont abordées : essais opérationnels et validation, applications à d'autres opérations d'hélicoptère et activités générales à bord des navires, et améliorations possibles permettant d'augmenter les capacités du système.

Colwell, J.L. 2004. Flight Deck Motion System (FDMS): Operating Concepts and System Description. TM 2004-003. DRDC Atlantic.

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1 Introduction

Landing a helicopter on a moving frigate in high seas is a challenging task. The Canadian Forces (CF) uses a combination of human operators and specialized equipment to perform flight operations in very high sea states, but there are some important human and equipment limitations that restrict these operations. The Flight Deck Motion System (FDMS) project was initiated to demonstrate that providing new information on ship motions in the form of a real time operator guidance system could improve the safety and efficiency of landings in high sea states. The primary function for the FDMS is to provide a 'Quiescent Period Indicator' (QPI), which identifies when ship motions are within operating limits and when they are not. The primary application for the FDMS is on CF frigates and destroyers, which is the focus for this document, but particular issues for CF Auxiliary Oiler/Replenishment (AOR) support ships are described where relevant.

The FDMS project is a direct consequence of the experience gained by DRDC Atlantic in supporting CF helicopter/ship flight deck certification trials, led by the Aerospace Engineering Test Establishment (AETE). In the years 1991 through 1994 DRDC Atlantic assisted AETE in performing flight deck trials with CH/124A Sea King helicopters on all CF classes of air-capable ships, including: HMCS OTTAWA, a St. Laurent Class frigate, or "steamer"; HMCS IROQUOIS, a DDH 280 or Tribal Class destroyer; HMCS PRESERVER, an AOR support ship; and, HMCS HALIFAX, a City Class, Canadian Patrol Frigate (CPF). In all cases, the ships encountered high seas on at least one occasion, where ship motions reached and exceeded limits for safe helicopter operations.

This Technical Memorandum identifies the requirements for a FDMS capability on CF ships and briefly describes two possible implementation plans; one as a relatively simple, stand-alone system, and the other as an integral part of existing or possible new shipboard systems. The primary goal for this document is to describe the FDMS in sufficient detail to enable its development, regardless of the implementation strategy. CF operational procedures for landing helicopters in high seas are reviewed, in order to provide context and to identify roles for the FDMS. Important new concepts are discussed, including how to quantify quiescent periods in real time, and what system capabilities are realistic for warning operators on operational limits with respect to current ship motions. System component locations are described, and operating modes are summarized. The acquisition and calculation of required ship motion parameters are discussed, and procedures for defining suitable motion criteria are described. Options for visual displays and system logic are described for the Quiescent Period Indicator (QPI), and alternative operating modes as a flight planning tool and as a flight deck data recorder are discussed. Finally, options for future work are discussed, including operational tests and possible system enhancements.

2 Requirements and Implementation Plan

2.1 Requirements

The primary goal for the FDMS is to provide better operator guidance to the shipboard Landing Safety Officer (LSO) for helicopter landings in high sea states. As discussed in References [1] and [2], the helicopter pilot and LSO are consistently successful at identifying when ship roll motions are ‘within limits’ for a safe landing, but cannot reliably identify when ship vertical motions are within limits. The initial application for the FDMS is to provide the LSO with new information on all relevant ship motions in a simple format, to allow a rapid assessment of ship motion limitations during the final landing phase (as discussed later in this document).

The primary reason for advocating development of the FDMS is to increase operational safety and efficiency, but it will also provide solutions for a number of existing problems on CF ships. The FDMS will remove current artificial constraints on the City Class ship motion “operational envelope” for helicopter landings, and it will resolve “unsatisfactory deficiencies” identified during flight deck certification trials on all three air-capable CF ship classes.

2.1.1 Remove operational constraint on CPF motion limits

The Sea King/CPF flight deck certification trial determined that flight deck vertical acceleration, FDVA, is a critical limiting parameter for hauldown landings in high sea states, but existing ship systems do not measure FDVA. As a consequence, an operational constraint is imposed on maximum ship pitch angle, in order to reduce the probability of encountering high levels of FDVA (paragraph 5.14.c, page 110 of [3]). If a system is provided to measure FDVA, then the maximum pitch angle will be increased from the constrained limit of 4° to 6°, which is the actual pitch limit established during the flight trial.

Based solely on pitch angle calculations [4], increasing the maximum limit from 4° to 6° translates into an increase of “limiting wave height” from about 4 metres significant wave height to 5 metres ($\approx 25\%$), for unidirectional waves. This corresponds to an increase of about 15% in “percent time operable”, for winter in the northern North Atlantic [5]. These measures of performance are somewhat simplistic, but they illustrate that the increase in pitch angle limits enabled by the FDMS would provide real and substantial benefits.

2.1.2 Resolve unsatisfactory deficiencies for visual aids

City Class: The Sea King/CPF flight deck certification trial (FDCT) report identifies an unsatisfactory deficiency with the ship's pitch and roll motion indicator (item 4 of 57 on a prioritized list of unsatisfactory deficiencies, described in paragraph 4.59, page 74 [3]). In summary, the report notes that the visual resolution of the ship's pitch and roll motion indicator display is too coarse for reliable use. The FDMS will not directly implement the recommended action, which is to modify the device's display; rather, the FDMS will provide a completely different way of visualizing motion limits, which is not subject to the resolution problems reported in this deficiency. This new approach is described in detail in following sections of this report.

Tribal Class: the Sea King/TRUMP FDCT report has two recommendations with respect to the display of ship motions (items 9 and 10 of 25 on the prioritized list of unsatisfactory deficiencies, described in paragraphs 4.05.a and 4.05.b, pages 36 and 37 of [6]). In summary, these deficiencies highlight that the existing ship motion display is unsatisfactory, and that a new means is required to "determine maximum ship motion at a glance". As for the CPF deficiency described above, the FDMS will not implement the specific actions recommended in the Tribal Class report, but will effectively solve these problems.

AOR Class: the Sea King/AOR Class FDCT report concludes that "the lack of pitch and roll (ship motion) displays in the FLYCO along with the lack of a method for determining ship heave was unacceptable" [7]. The role of FLYCO in helicopter operations is explained in Section 3. The FDMS would explicitly resolve this problem.

2.2 Implementation plans: stand-alone vs. integrated

There are two likely approaches for implementing a FDMS capability on CF ships: either (i) as a relatively simple, stand-alone system; or, (ii) as an integral part of existing or possible new shipboard systems. In either case, the most likely future role for DRDC Atlantic is to act as an advisor to industry for the definition, development and testing of these possible future systems. The primary goal for this document is to describe the FDMS in sufficient detail to enable its development, regardless of the implementation strategy.

The remainder of this document describes the FDMS as a stand-alone system, but the most likely approach for implementation may be as an integral part of new systems which will likely be developed for the Sea King replacement helicopters being acquired through the Maritime Helicopter Project. The key features of the FDMS described in following sections will not be significantly different for either approach.

3 Flight Deck Operations

The main focus for the Flight Deck Motion System (FDMS) is to provide improved operator guidance on ship motions for landing helicopters on frigates and destroyers in high sea states. The limiting factors affecting this operation are reviewed, and the process used for hauldown landings is described, to provide context for a description of the roles performed by the FDMS.

3.1 Limiting Factors

The primary factors limiting helicopter/ship operations are:

- pilot workload;
- aircraft limits (power, control, etc);
- relative wind speed and direction;
- wind turbulence; and,
- ship motions.

Pilot workload is directly affected by the other four factors in this list, and is also influenced by other considerations, such as visibility, aircraft loading, and the status of flight augmentation systems. The focus for this document is ship motion effects, but there are many other important, limiting factors, as discussed in [1].

All flight operations are restricted by “relative wind”, which is the vector sum of true wind speed and direction with ship speed and course relative to the wind. An example relative wind envelope for helicopter landing is shown in Figure 1. The relative wind diagram uses polar coordinates with angle denoting relative wind direction (deg) and radius denoting relative wind speed (kt). Following standard CF practice, relative direction is defined as *Red* or *Green*, corresponding to relative wind direction from the Port or Starboard sides of the ship, respectively. The shaded regions of Figure 1 define the relative wind envelope: any combination of conditions which provides relative wind speed and direction within the envelope is acceptable; and, all points outside of the relative wind envelope are not acceptable.

The relative wind envelope is defined by flight testing, and incorporates the effects of pilot workload, aircraft limits and wind turbulence. The relative wind envelope is specific to both the type of helicopter and the type of ship for which it was developed, and is also specific to the operation being performed. The example shown in Figure 1 is representative of a Sea King helicopter landing on a Canadian Patrol Frigate (CPF).

Helicopter Relative Wind Operational Envelope

radius= relative wind speed (kt) **angle** = relative wind direction (deg)

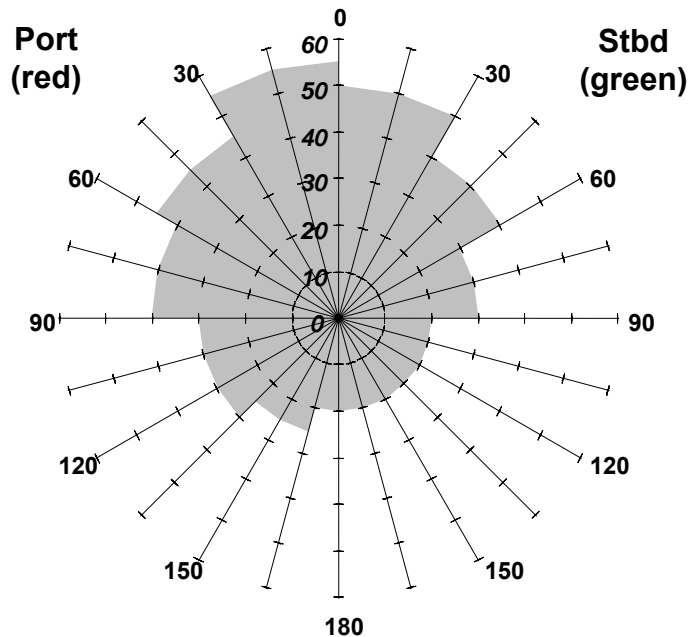


Figure 1: Example relative wind envelope.

The relative wind envelope is not symmetrical with respect to port and starboard wind directions, due to the location of the Sea King tail rotor on the port side of the tail boom. For red relative wind (i.e. from the port side of the ship and helicopter), the flow of wind over the tail rotor is unobstructed, while for green relative winds, from starboard, the tail rotor is partially obstructed by the tail boom, resulting in reduced effectiveness. Wind envelopes for some operations are symmetrical with respect to wind direction, such as folding the helicopter's blades before transit to the hangar.

In high seas, helicopter operations are limited by both the relative wind envelope and by ship motions, and in some conditions, by heavy spray. Section 4 on quiescent period concepts and Section 5 on ship motion parameters discuss how ship motion limits are currently defined for traditional ship/helicopter operating limits (SHOLs), and describe a new methodology for specifying ship motion limits for the FDMS. The remainder of this section describes the helicopter landing process and how the FDMS would be used.

3.2 Hauldown Landings in High Seas

The Canadian Forces operates CH-124A Sea King helicopters from its twelve City Class frigates and four Tribal Class destroyers. Operations in high seas are aided by the recovery assist, secure and traverse (RAST) system, from Indal Technologies Incorporated. CF Sea King helicopters are also operated from the

CF's two AOR support ships, but they do not have RAST systems, and so their high sea state capability is relatively limited. The key difference in helicopter operations between ships with and without RAST is the ability to secure and handle the helicopter once it has landed. With RAST, the helicopter is secured very rapidly, and so the operators can take advantage of relatively short-duration quiescent periods (as discussed later). Without RAST, the quiescent period should be of sufficiently long duration to secure the helicopter with lashings - long-duration quiescent periods become relatively scarce as sea state increases.

3.2.1 Recovery assist, secure and traverse (RAST) system

The main components of the RAST system which are involved in landing and securing the helicopter are:

- (i) the *hauldown cable*, which attaches the flying helicopter to a constant-tension winch located inside the ship, immediately below the touchdown point on the flight deck;
- (ii) the *rapid securing device* (RSD) on the flight deck, which secures the landed helicopter by grabbing the helicopter's *main probe*, see Figure 2;
- (iii) *tail guide bars* on the aft surface of the flight deck, which form slots aligned fore and aft into which the helicopter's *tail probe* falls and secures the helicopter against yawing around the main probe; and,
- (iii) the RAST control console, where the Landing Safety Officer (LSO) observes flight operations and controls the RAST system.

Other RAST components include two *tail guide winches* at either side of the aft end of the flight deck for straightening the secured helicopter, and the recessed *deck track* which secures the RSD and allows it to travel between the flight deck and hangar. City Class frigates have a single RSD and track system, and Tribal Class destroyers have two RSDs and two track systems.

Once connected, the hauldown cable extends from the winch, upwards through a faired *bellmouth* opening in the flight deck, through the RSD, and into the helicopter through its main probe, as shown in Figure 2. During landing and take-off, the RSD is parked over the bellmouth, and so the hauldown cable runs from the winch, through the RSD, and into the helicopter. Once the helicopter has landed, the RSD secures the helicopter by grabbing the probe between two parallel arresting beams, or *jaws* (hence, the common name "bear trap"), and the cable is released. After the helicopter has been straightened to align with the ship's fore and aft centreline, and the rotors have been folded, the RSD traverses the helicopter into the hangar by moving along its securing tracks.



Figure 2: Helicopter hovering over RSD, hauldown wire attached.

The hauldown system does not literally pull the helicopter out of the air, rather it applies downward tension which causes the helicopter to behave like an inverted pendulum. This provides “seat of the pants” physical cueing for the pilot, as the bottom of the aircraft is generally oriented towards the RSD. The typical hauldown cable tension is approximately 10 % of the helicopter’s weight. It is common for the helicopter to climb away from the flight deck while the cable is under tension, and it is quite possible, though not so common, for the helicopter to touchdown outside of the RSD capture zone, in which case the hauldown cable extends horizontally from the RSD to the helicopter probe.

3.2.2 Landing Process

The landing process is controlled by the helicopter pilot, in partnership with the Landing Safety Officer (LSO) and Flight Deck Coordinator (FLYCO). The LSO is located in a compartment called the *howdah*¹, which provides a view from below the hovering helicopter, and FLYCO is located in the Flight Deck Control Room (FDCR), which overlooks the flight deck from a position high on the port face of the hangar. Figure 3 shows the locations of the howdah and FDCR on a CPF. The arrangement on a Tribal Class is very similar to the CPF. The AOR Class has a FDCR in a similar location, but does not have a howdah.

¹ howdah: “seat or covered pavilion on the back of an elephant or camel” (Merriam-Webster)

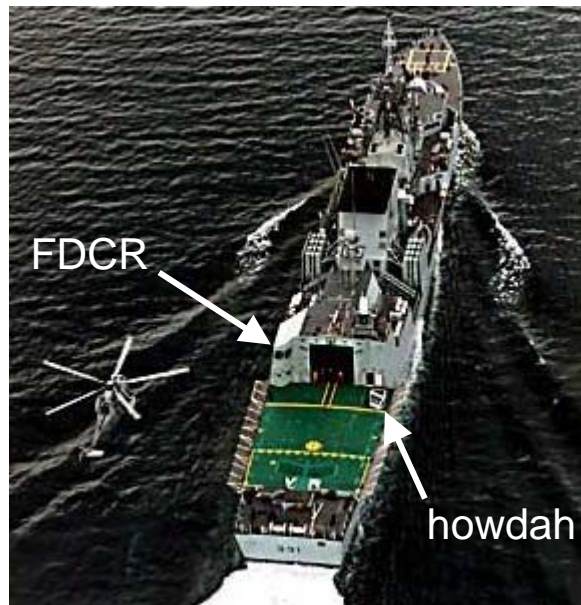


Figure 3: Locations of FDCR and howdah.

The LSO controls the RAST system, provides guidance to the pilot on position-keeping with respect to the centre of the RSD, and assesses ship motion limits at the time of landing. FLYCO controls signal lights mounted on the hangar face, coordinates firefighting, and performs a variety of other tasks.

The sequence of steps for a hauldown landing in high seas is summarized below.

- the helicopter approaches the ship from astern on the ship's port side
- the helicopter hovers across the ship to the starboard side of the flight deck
- the helicopter lowers a messenger cable to the flight deck
- the messenger cable is electrically grounded by flight deck personnel
- the hauldown cable is attached to messenger cable by flight deck personnel
- the hauldown cable is raised into and attached to the helicopter
- the pilot takes a "high hover" position over the RSD, where
 - tension is applied to the hauldown cable, and
 - the pilot waits for a "quiescent period"
- the pilot initiates descent to "low hover"
- the pilot requests clearance to land from the LSO
- the LSO will usually either
 - grant clearance to land
 - advise the pilot to re-position to keep centred over the RSD
 - advise the pilot to wait for ship motions to reduce, or
 - call a "wave off", after which the pilot returns to high hover

A detailed description of this process is provided in the Shipborne Helicopter Operating Procedures (SHOPS) manual [8], which defines procedures and operating limits for CF maritime helicopter operations.

3.3 Roles for the FDMS

As briefly described earlier, the primary purpose for the FDMS is to provide a Quiescent Period Indicator (QPI), to help the LSO identify when ship motions are within operating limits and when they are not. The FDMS also has secondary roles for providing statistical information on ship motions for flight planning, and as a flight deck data recorder, which stores ship motions whenever the system is turned on. These different FDMS capabilities are described here in terms of their roles for supporting flight deck operations. Subsequent sections provide more details on the underlying concepts and technologies.

3.3.1 Quiescent Period Indicator (QPI)

The critical time for operator guidance on quiescent periods is the interval between the pilot's descent to low hover and the pilot's request for permission to land. During this time, the LSO's attention is focused on advising the helicopter pilot to stay in position over the RSD, ensuring that no personnel or foreign objects are in the way, and operating the RSD. Any information on ship motions other than from "the seat of the pants" must allow the LSO to "determine maximum ship motion at a glance", as stated in Section 2.1.2. The QPI display (described later) has been devised to satisfy this requirement for ease of use, and to resolve the ship motion information deficiencies identified in Section 2.1.2. This information can be integrated into existing procedures, by simply replacing existing ship motion instruments in the howdah with the FDMS display (or by incorporating the FDMS display in new RAST control systems which may be developed in the future).

The QPI can also play a valuable role in advising when ship motions are out of limits while the helicopter is at high hover, provided that there is a viable method for warning the pilot. This role is desirable, as it should reduce the number of wave offs which occur when the helicopter descends to low hover while vertical accelerations are high, and it should reduce the incidence of high-torque engine transients [9], which affect time-between-failure and maintenance. This information can be integrated into existing procedures when radio use is allowed (the LSO can simply provide verbal warnings to the pilot), but does not seamlessly integrate with existing procedures for 'silent' operations. Current CF procedures involve relatively few radio exchanges between the pilot and LSO, and are readily adaptable to silent operations. In this case, the hangar face 'trafficator' lights controlled by FLYCO provide visual cues to the pilot: the lights switch from red to amber when the hauldown system is hooked up and ready to assist in landing; and, the lights switch from amber to green when the

LSO gives clearance to land (i.e. the helicopter is in position at low hover and everything is 'in order'). The time between amber and green is described in the preceding paragraph. In order to advise the pilot that the deck is out of limits (probably for vertical motions) without radio contact, existing procedures would have to be modified. It would be possible to delay the light change from red to amber until motions are within limits; but, this implies that the trafficator lights should go from amber to red if motions subsequently exceed limits.

The current concept of operation for the QPI is to provide a 'passive' source of information to the LSO. Many other possible ways of providing ship motion information to the LSO and/or pilot can be explored in the future.

3.3.2 Flight planning information

An alternate role for the FDMS is to provide statistical information on ship motions for input to flight planning. In particular, this information can help the flight planners to determine if ship motions are generally too severe for flight operations, and/or to identify ship tactics (i.e. speed and course) which minimize ship motions. In order to gather reliable statistics, the ship must maintain the speed and course being evaluated for 'flying stations', and so this mode of operation imposes some restrictions on ship handling. In typical circumstances, with seas within $\pm 30^\circ$ of the bow and ship speed above 10 knots, this would require about 10 minutes (as discussed later), but can require considerably longer for low ship speeds or for waves aft of the beam. It should be possible to combine the FDMS with a description of the seaway and a method for calculating ship motions to provide a "what if" advisory capability. This would permit assessment of best and worst combinations of ship speed and course selections without having to actually take those speeds and headings, but this is a topic for possible future work.

3.3.3 Flight deck data recorder

While operating, the FDMS continually measures and displays ship motions. The flight deck data recorder capability is provided by simply saving the motions data (and time stamps) to computer disk, as described later. These data can be used to determine if an unexpected event was related to ship motions, provided that the time of the event is known, and the flight deck data recorder mode was operating.

3.4 Other helicopter operations

Ship motions can limit a variety of helicopter operations, including the following:

- hauldown landing, all helicopter systems functioning (current focus);
- freedeck landing, with RSD to rapidly secure helicopter;
- freedeck landing, with no RSD;

- helicopter in-flight refueling (HIFR);
- vertical replenishment (VERTREP);
- helicopter on-deck: straightening, folding blades, folding tail boom, etc.;
- personnel on-deck: hauldown wire hookup, handling stores & weapons;
- helicopter transit to and from hangar; and,
- helicopter maintenance (especially engine replacement).

From the FDMS perspective, the key difference between these operations is the definition of ship motion limits, or criteria. As discussed later, there is a general scarcity of data for defining ‘real time’ criteria, but the FDMS provides one part of the solution: the flight deck data recorder will provide the ship motion data. The other part of the solution is for the LSO and other personnel involved in helicopter operations to observe and record events (and times) when ship motions appear to limit operations. Over time, a considerable amount of new information on limiting conditions can be obtained and analyzed, and new criteria can be developed for a variety of helicopter operations.

4 Concepts and System Overview

This section begins with a description of how quiescent periods are defined in real time for the FDMS, and presents rules for classifying and changing between different *states of quiescence*. This section continues to discuss the types of warnings that the FDMS can provide to the operator, and also highlights the types of warnings that it cannot provide. Finally, major system components are described, and their recommended locations identified.

4.1 Quiescent periods in real time

In general, a quiescent period is the interval of time when all ship motions are within acceptable limits for performing a desired activity - in this case; landing the helicopter. It is simple to define when the deck is ‘out of limits’, but it is not so simple to define when it is back, ‘in limits’. If only the instantaneous motion amplitudes are considered, the *state of quiescence* of the flight deck can oscillate between quiescent and not-quiescent, as large-amplitude, periodic ship motions pass through zero, as shown in Figure 4a.

Figures 4a and 4b both show the same 40 seconds of ship motion data, using flight deck vertical acceleration (FDVA) data measured during Sea King/City Class flight deck trials. The maximum and minimum motion limit values are labeled on the left sides of each vertical axis, and the red/green horizontal *colour bars* located immediately below each horizontal time axis show the *state of quiescence* defined by FDVA, with *red* for not quiescent, and *green* for quiescent.

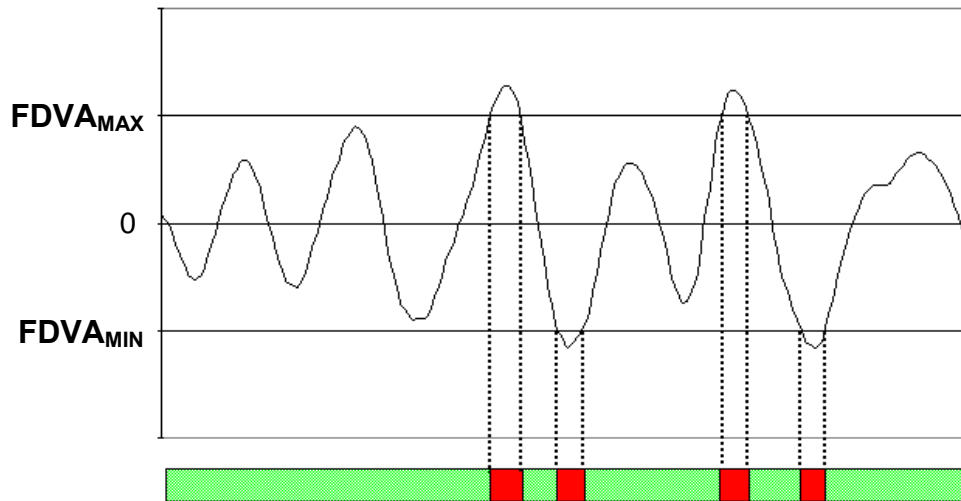


Figure 4a: Oscillating between quiescent and not quiescent.

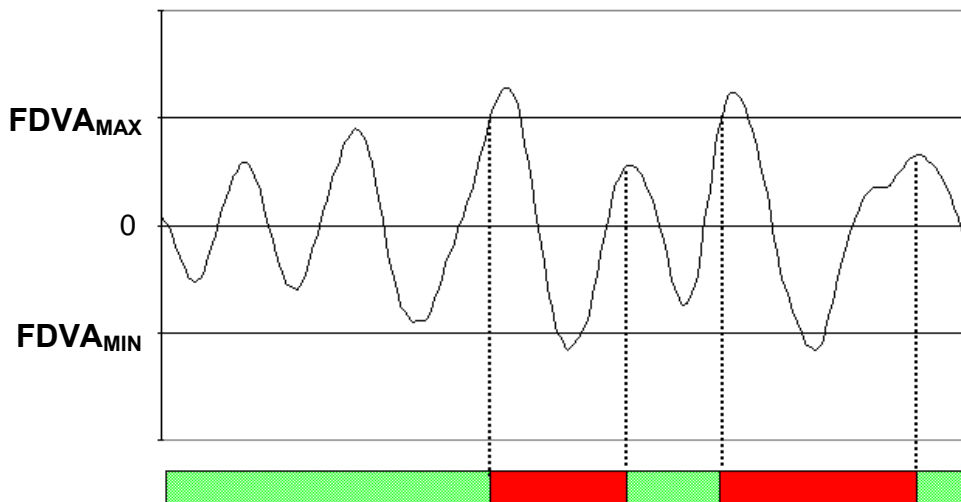


Figure 4b: Delay start of quiescent period until peak within limits.

The duration of the shortest quiescent period shown in Figure 4a is 2 seconds, which is far too short for a successful helicopter landing (as discussed later). Thus, it is important to avoid rapid and sequential changes from not-quiescent to quiescent as the motions pass through zero during high amplitude motion cycles. In order to prevent this problem, the following rules for changing quiescent state are defined.

- (i) The state of quiescence changes from quiescent to not-quiescent at the instant when the limit for any one motion parameter is exceeded; and,
- (ii) the state of quiescence changes from not-quiescent to quiescent only after each motion parameter which has exceeded its limit experiences a subsequent motion peak below that limit.

This two-part rule is applied to the example ship motions in Figure 4b, at the bottom of Figure 4. The rapid oscillation between quiescent states shown in Figure 4a is avoided by delaying the change from not-quiescent to quiescent until after an ‘acceptable’ peak value has been encountered.

The example in Figure 4 shows only one motion parameter for two states of quiescence. The remaining parts of this section provide increasingly complex examples by first considering two different ship motion parameters for two possible states of quiescence (*red* and *green*), and then considering two ship motions for three possible states of quiescent (*red*, *yellow*, and *green*). The general implementation of the FDMS will be capable of handling an arbitrary number of ship motions for three states of quiescence. The rules developed for defining and changing quiescent states are summarized at the end of this section.

4.1.1 Two quiescent states: *red* and *green*

Figure 5 shows an example of changing quiescent states for two ship motion parameters, with two possible states of quiescence: *red* and *green*. The top panel shows two minutes of roll angle data and the bottom panel shows FDVA data for the same time. These motions were measured during Sea King/City Class flight deck trials, and were used in conjunction with measured helicopter parameters to illustrate quiescence and to define ‘real time’ ship motion criteria in Reference [2]. The roll and FDVA ‘max’ and ‘min’ limit values shown on this and subsequent figures (as well as previously on Figure 4) are representative, real limits for the Sea King helicopter operating on the City Class.

The horizontal colour bars immediately below each panel show the state of quiescence as determined by that ship motion parameter alone: with QP_{ROLL} below the top panel; and, QP_{FDVA} immediately below the bottom panel. The second colour bar below the bottom panel is a copy of QP_{ROLL} , and the bottom-most colour bar is the overall state of quiescence defined by combining the roll and FDVA quiescent periods. The start and end of each quiescent period (i.e. the transition between *green* and *red*) is connected to its source by a vertical arrow. The states of quiescence from each separate motion evaluation are combined to define the overall state of quiescence according to the *precedence* of each state, with *red* having precedence over *green*. In other words, if any state is *red*, then all states are *red*.

The *rules of precedence* are used as follows, using the operator \mathbf{x} to denote combining quiescent states.

$$\begin{aligned} red \mathbf{x} green &= red \\ green \mathbf{x} green &= green \end{aligned}$$

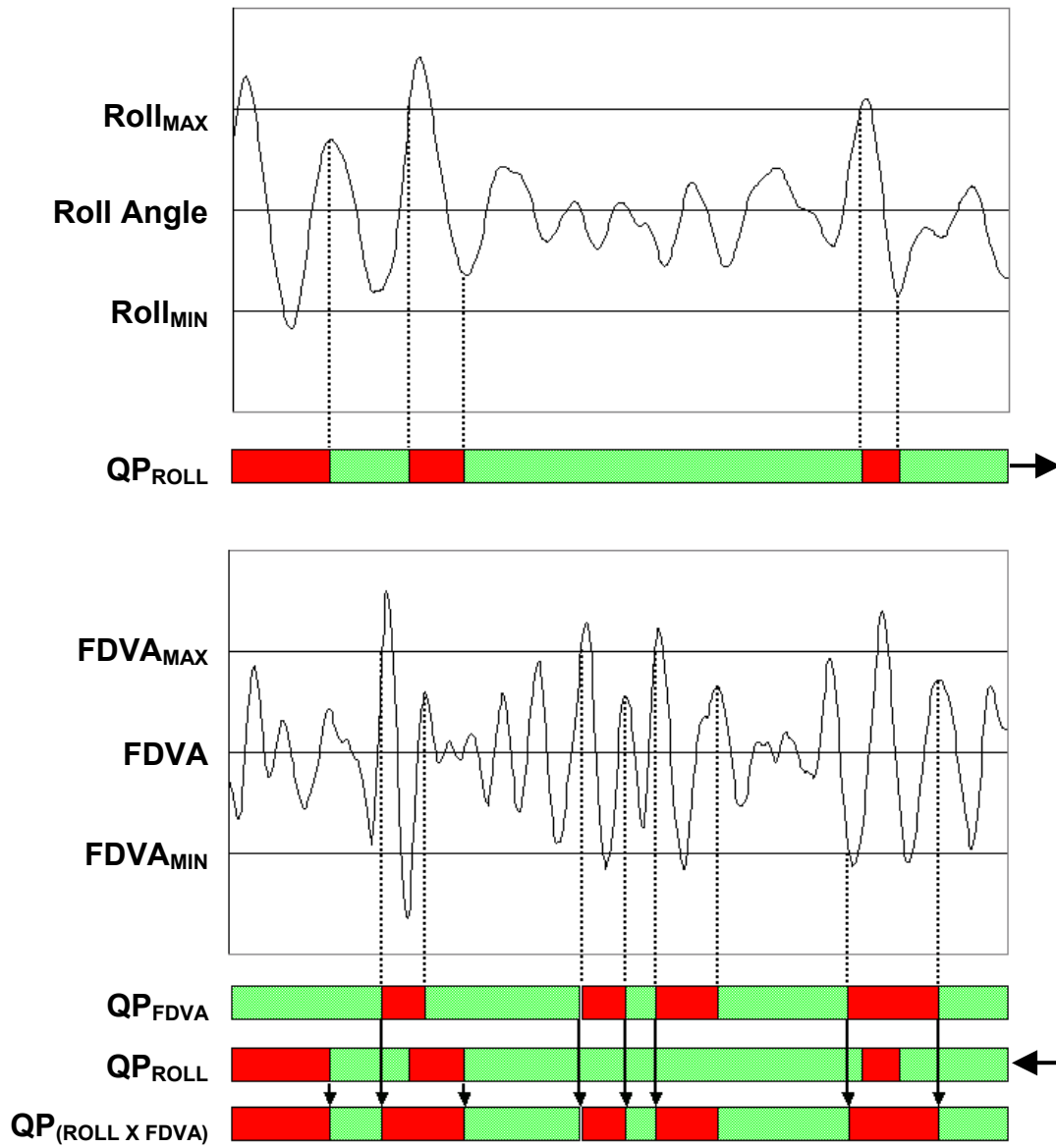


Figure 5: Two quiescent states (red and green) for two ship motion parameters.

4.1.2 Three quiescent states: *red*, *yellow* and *green*

Figure 6 shows an example of changing quiescent states for two ship motion parameters, with three possible states of quiescence: *red*, *yellow*, and *green*. The *yellow* state is introduced to indicate caution: the flight deck is within limits, but at least one motion parameter is very close to its limit, and so there is an increased probability of transition between *green* and *red*. The quiescent state colour bars in Figure 6 are defined and combined and using the generalized *rules governing states of quiescence*, which are defined in the next section.

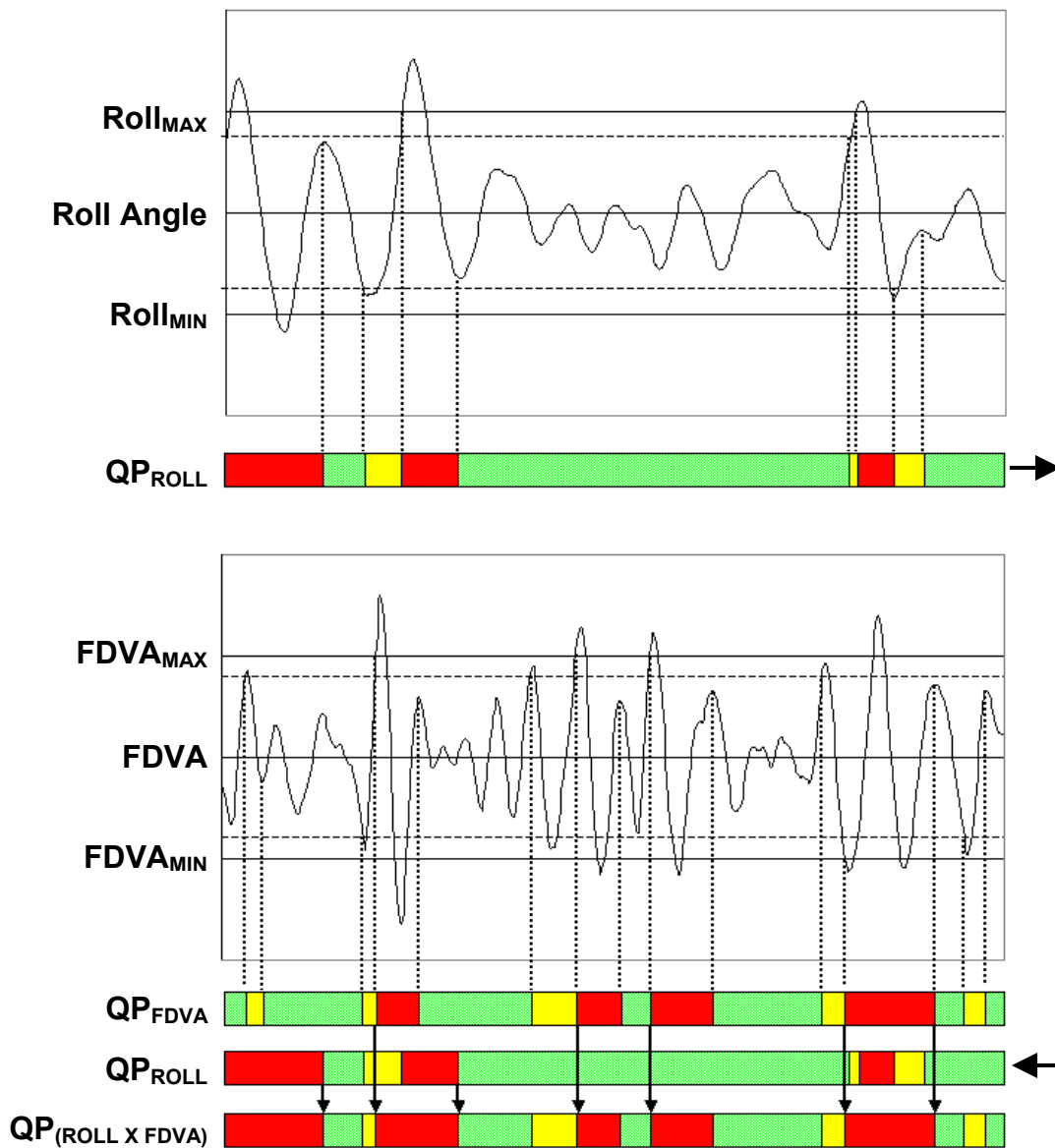


Figure 6: Three quiescent states (*red*, *yellow* and *green*) for two ship motion parameters.

4.1.3 Rules governing states of quiescence

The four rules for defining, ordering, changing, and combining states of quiescence are defined below. These rules are expressed for three states of quiescence (*red*, *yellow* and *green*), but are sufficiently general for any two or more states.

.....

Rule 1: States of quiescence

There are three states of quiescence: *red*, *yellow* and *green*.

.....

Rule 2: Order of precedence

The order of precedence for the states of quiescence is, from highest to lowest: *red*, *yellow* and *green*.

.....

Rule 3: Changing the *state of quiescence*

- (i) the state of quiescence for any motion parameter changes from a lower state of precedence to the next higher state of precedence at the instant when the limit for that motion parameter is exceeded; and,
 - (ii) the state of quiescence for any motion parameter changes from a higher state of precedence to the next lower state of precedence only after that motion parameter experiences a subsequent motion peak below its limit.
-

Rule 4: Combining *states of quiescence*

At any instant of time, the combined state of quiescence of two or more motion parameters is equal to the state of the motion parameter which has the highest precedence.

.....

Rule 4 is commutative (i.e. not sensitive to order). For example, using the operator **X** to denote combining quiescent states:

$$\begin{aligned} \text{red X green} &= \text{green X red} &= \text{red} \\ \text{red X yellow X green} &= \text{red X green X yellow} = (...) = \text{red} \\ \text{green X yellow} &= \text{yellow} \end{aligned}$$

4.2 FDMS capability and reliability

In order for CF operators to gain and maintain confidence in the FDMS, there must be a clear understanding of the system's capabilities, and it must be reliable.

The initial capabilities of the FDMS are straightforward: it is designed to warn the LSO when the flight deck is not quiescent (*red*), and when it is near the limits (*yellow*). When the FDMS indicates the flight deck is quiescent (*green*), it does not imply nor guarantee that it will remain quiescent for long enough to perform any particular task, it simply indicates that *under current conditions*, the flight deck is within limits. These conditions are summarized below, in terms of the flight deck being 'in' and 'out' of limits:

red = warning the flight deck is out of limits;
yellow = caution the flight deck is within limits, but close to the limits; and,
green = the flight deck is in limits.

With existing CF procedures, there are times that the pilot attempts to land when the deck is out of limits for vertical acceleration (as discussed in [2] and [9]), which implies that neither the pilot nor the LSO are aware of the situation. The FDMS is devised to avoid this situation by providing a reliable indication of flight deck quiescence. In order to demonstrate that it is reliable, the FDMS must minimize the number of false warnings that it produces, and should also attempt to minimize the number of very short quiescent periods that it identifies.

4.2.1 Reliability: false warnings

A false warning occurs when the FDMS indicates that the conditions are out of limits (*red*), but there is no reason related to ship motions that would prevent a safe landing. This represents a lost opportunity, and the occurrence of a false warning implies that the ship motion criteria are not valid or not complete.

The key steps for avoiding false warnings are: (i) measure all relevant ship motions; and, (ii) apply valid criteria. The limits on roll angle and vertical acceleration derived from existing operational data [2] should provide a good starting point for operational criteria. As experience is gained and more data are acquired, it may be reasonable to refine these limit values and to establish limits for additional motion parameters, but new criteria should not be introduced until they have been validated.

A false caution (*yellow*) condition can exist, but is not as serious as a false warning, as it simply indicates that a certain percentage of the limit value has been reached. If operators believe that the *red* limit value for a particular motion parameter is suitable but that false cautions are being produced, then its *yellow* limit value can be modified. The FDMS configuration will allow different *yellow* limits for each motion parameter, as described later in Section 6.2.

4.2.2 Reliability: quiescent period duration

The onset of a quiescent period does not imply that the overall duration of the quiescent period will be long enough to accomplish the activity. Attempting to land at the start of a quiescent period which is too brief to complete the landing can be unsafe, unless the attempted landing is abandoned. This situation already occurs with existing procedures, and usually results in a wave-off, either initiated by the pilot by voluntarily climbing to high hover, or by the LSO by 'calling' a wave-off. The informal consensus reached in discussions with CF fleet and test pilots is that quiescent periods of less than 4 seconds duration are too short for hauldown landings, and those over 6 seconds duration would usually be satisfactory.

The rules governing quiescence enable the FDMS to avoid rapid changes from *red* to *green* between large amplitude peaks of individual motion parameters, but do not prevent rapid changes between *red* and *green* states due to different motion parameters changing state at or near the same time. For most ships, including monohull frigates and destroyers, vertical and lateral motions have characteristically different frequency responses: vertical motions are relatively broad-banded, and so the vessel responds at the wave encounter frequency; while lateral motions are relatively narrow-banded, with the predominant response at the ship's natural roll period. The main consequence of this behaviour is that one motion parameter can become or remain quiescent while a different motion parameter goes out of limits, and so very short quiescent periods do exist in reality. The *yellow* state should reduce the number of times that landings are initiated near the beginning of brief quiescent periods, but it will not likely eliminate them.

4.2.3 Visible vs. audible warnings

A variety of visible and audible technologies are readily available for warning the LSO of a change in conditions. The informal discussions with CF fleet and test pilots mentioned earlier on quiescent period duration were also used to discuss the relative merits of visible and audible warnings. There were almost as many concepts for visual warnings as there were discussions, but there was unanimous agreement on audible warnings - they should not be used. The FDMS concept described here is based on a passive visible warning technology, using the *quiescent period indicator* (QPI) described in Section 5. The QPI display is considered to be passive, as it is located out of the LSO's normal line of sight (i.e. the helicopter), and so the LSO must look down to see it. An example of an active visible warning would be a QPI display imposed directly in the LSO's line of sight, using a 'heads up display' technology. This technology is not considered for the 'stand alone' FDMS system described here, but it could be a viable option for incorporating the FDMS capability in a totally new RAST control system.

4.3 FDMS components and locations

Figure 7 shows the FDMS major components and their recommended locations for a City Class frigate.

The FDMS consists of four major components: a ship motion sensor unit, located inside the ship directly below the helicopter landing point; a data processing computer, located near to the sensor unit; and, two visual displays, one in the howdah for the LSO during flight operations, and another in the Pilot Ready Room, for pre-flight briefings. The arrangement for a Tribal Class destroyer would be essentially the same as shown in Figure 7, but AOR ships do not have a

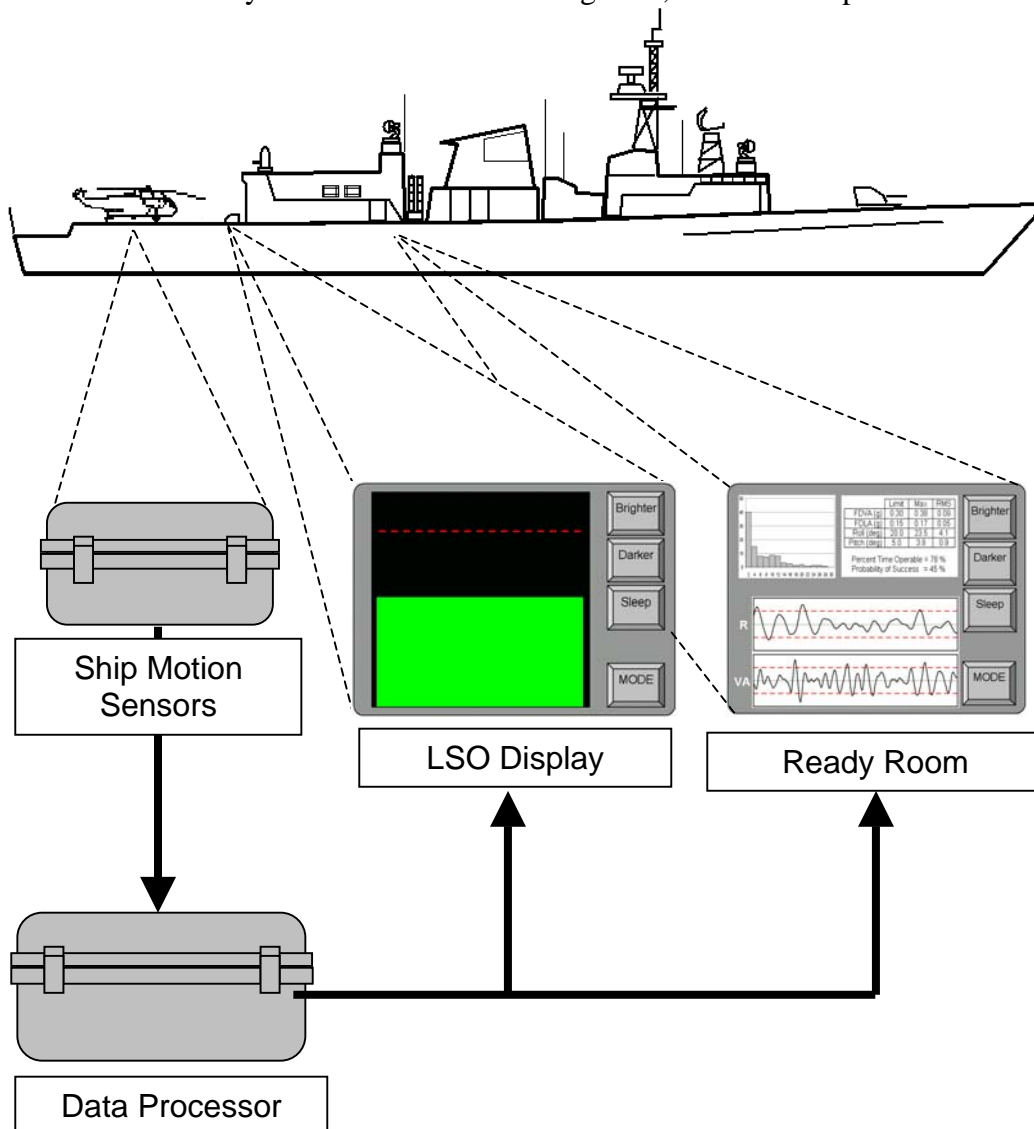


Figure 7: FDMS major components and locations for a City Class frigate.

howdah, and so the LSO display would be in the Flight Deck Control Room (FDCR), where the LSO is located.

4.3.1 COTS solutions

The technologies for motion sensing, data acquisition, computer processing, and display which are required to support the baseline FDMS configuration described in this document can be satisfied by existing, commercial off-the-shelf (COTS) products. The DRDC Atlantic ship motion sensor system [10] illustrates one possible solution for both motion sensors and data processing, as discussed in Section 6.1, but many alternate configurations would also be viable.

5 Operating Modes

The FDMS has three operating modes:

1. quiescent period indicator (QPI);
2. flight planning information; and,
3. flight deck data recorder.

The quiescent period indicator (QPI) displays all relevant ship motions in a simple format, to allow a rapid assessment of ship motions during the final landing phase. The flight planning information mode provides descriptive statistics on recent ship motions, to assist decision making during flight planning. When the flight deck data recorder mode is selected for operation, then it runs continuously in the background during both QPI and flight planning modes. The remainder of this section contains detailed descriptions of the FDMS operating and display modes, followed by an overview of operator input, and the arrangements for switching video displays and active command screens.

The stand-alone FDMS concept described here uses touch-sensitive display screens, and so operator input is made by pressing “virtual buttons” which are displayed on the screen. This is the most simple way to implement the system, but the same operating and control strategies could be implemented for other human-machine interfaces, such as keyboard/trackball or multi-switch panels, which might be used for an integrated FDMS/RAST system.

5.1 Quiescent Period Indicator (QPI)

There are two display modes which indicate the current state of quiescence: one called the *ship motions display*, which shows a number of separate ship motion parameters on the screen at the same time; and another called the *quiescent period indicator (QPI)*, which shows the state of quiescence for all ship motions at a

single glance. The QPI is a novel technique for displaying quiescence and is the essential core of the FDMS for real time operator guidance; however, the ship motions display is described first, as it is the basis for making the quiescent period display.

The quiescent period indicator display modes assume that the operator can distinguish between red, yellow and green colours. This is a good assumption for the LSO on CF ships, as the LSO is a pilot who must pass colour vision tests, but it may not be a good assumption for all navies.

5.1.1 Ship motions display

Figure 8 shows an example ship motions display for the quiescent period indicator. There are two main screen areas; a relatively large motions display area, and a smaller controls area on the right hand side of the display. Options for operator input and system control are discussed at the end of this section.

Figure 8 is a static snapshot of a time-varying display. Each of the six vertical bars represents a different ship motion parameter. At any instant of time, the bar colour indicates the quiescent state and the bar height, $h(t)$, indicates how close the current amplitude, $X(t)$, is to its limit values, X_{MAX} and X_{MAX} , as follows for motion parameter i .

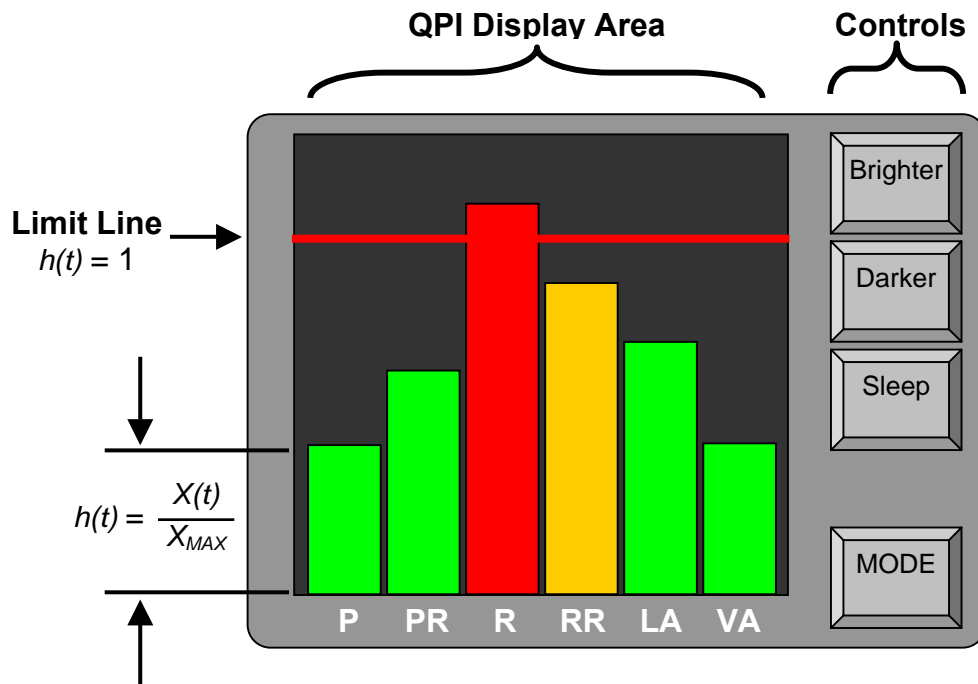


Figure 8: Quiescent period indicator, ship motions display.

$$\begin{aligned}
h_i(t) &= X_i(t) / X_{i(MAX)} , & \text{for } X_i(t) > 0 \\
&= 0, & \text{for } X_i(t) = 0 \\
&= X_i(t) / X_{i(MIN)} , & \text{for } X_i(t) < 0
\end{aligned}$$

where, $h_i(t)$ is the normalized bar height at time t , $X_i(t)$ is the motion amplitude at time t , $X_{i(MAX)}$ is the maximum limit for positive $X_i(t)$, and $X_{i(MIN)}$ is the minimum limit for negative $X_i(t)$.

The FDMS uses a right-handed Cartesian coordinate system with the following axes: longitudinal axis X , positive forward; lateral axis Y , positive to port; vertical axis Z , positive up; roll angle about the X axis, positive for starboard side down; pitch angle about the Y axis, positive for bow down; and, yaw angle about the Z axis, positive for turning to port. All motions have nominal mean values of zero, and so positive and negative amplitudes denote motion direction. For example, maximum and minimum limit values for roll angle define the maximum magnitudes for rolls to starboard and to port, respectively. All maximum limit values, $X_{i(MAX)}$, are positive and all minimum limit values, $X_{i(MIN)}$, are negative, so that $h(t)$ is always positive.

For all parameters, the normalized bar height varies from $h(t)=0$ at the bottom of the display window to $h(t)=1$ at the *Limit Line*, which extends across the display near the top of the window. The limit line is at a fixed position, so that the top of a bar will go “off screen” if its motions exceed the limit by a large amount.

In Figure 8, the first bar represents pitch angle (P), which is less than 50% of its limit and coloured green, while roll angle (R) in the third bar exceeds its limit, and is coloured red. The six motion parameters shown in Figure 8 are, from left to right, pitch angle (P), pitch angular rate (PR), roll angle (R), roll angular rate (RA), lateral acceleration (LA), and vertical acceleration (VA). This simplified motion labeling scheme is based on common terms used by aircrew for naming ship motions, as discussed further in Section 6.1.

As time progresses, the height of each bar changes in real time with motion amplitude, and so the rate of change of bar height can be used as a third indicator of motion tendencies. Since the ship usually takes a heading near head seas for helicopter operations, the frequency of vertical ship motions (pitch and heave) are generally higher than the frequency of lateral motions (roll and sway). Thus, the bars representing vertical motions would normally be changing height more rapidly than those for lateral motions.

The main purpose for the QPI ship motions display is to enable the LSO to examine a number of discrete motion parameters simultaneously, to determine if only one or perhaps many motion parameters are limiting operations. If only one or a few related parameters are going ‘out of limits’, then it may be possible to increase the number and/or duration of quiescent periods by a simple change in ship tactics. For example, if vertical acceleration appears to be the dominant

cause for the deck being out of limits, then a reduction in ship speed may be beneficial. Alternately, if roll angle seems to be the dominant parameter, then altering course towards head seas may be beneficial.

5.1.2 Quiescent period indicator (QPI) display

The quiescent period indicator (QPI) display uses a single vertical bar to represent the overall quiescence of the flight deck. Figure 9 shows an example QPI display developed from the six-parameter ship motions display example of Figure 8. The colour of the QPI's single bar is defined using the rules for order of precedence and combining states of quiescence defined in Section 4.1.3. Since at least one of the parameters in Figure 8 is *red*, then the combined state for the single bar in Figure 9 is also *red*. The height of the quiescent period display bar is set equal to the highest normalized value of all parameters; in this case, roll angle.

The limit line in Figure 9 is mostly obscured by the QPI display bar, but it occupies the same position as shown in Figure 8. As time passes, the limit line will become more obvious when the bar height reduces below $h(t)=1$, but the colour of the bar will remain *red* until part (ii) of the rule for changing quiescent states is satisfied. If any other parameter goes out of limits before a relatively low amplitude peak in roll angle is encountered, then the bar will remain *red*, and its height will be reset to match that of the highest normalized value. The general process for updating the quiescent period display is discussed below.

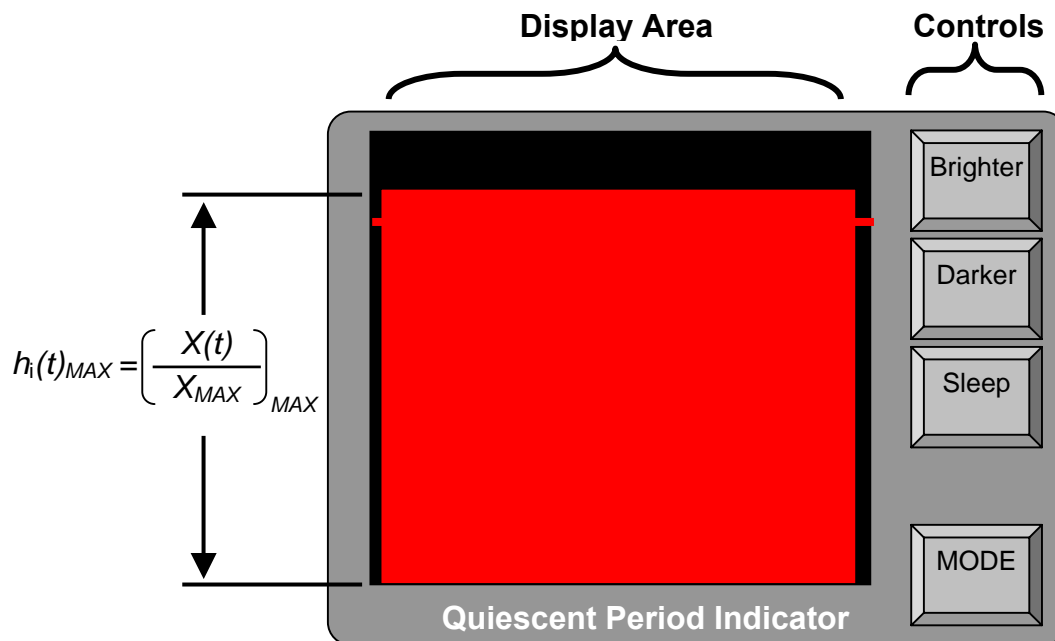


Figure 9: Quiescent period indicator, quiescent period display.

5.1.3 Evaluation process for changing state of quiescence

The QPI display is updated using a continuous process which is synchronized with the ship motion data acquisition process (see Section 6.1). Immediately after a sample *sweep* is performed (i.e. all motion channels are sampled), the motion parameters are evaluated to determine if a change in quiescent state is required, using the criteria described later in Section 6. Changing quiescent state from a lower to higher order of precedence (i.e. *green* > *yellow* > *red*) has priority. The first instance of a parameter changing state to a higher level than currently shown on the display causes the display to update immediately, to show the appropriate new bar colour and new bar height. If the new quiescent state is *yellow*, then the remaining parameters are evaluated to determine if the state increases from *yellow* to *red*, and then the motion amplitudes are examined to determine if bar height should be increased. If there is no increase in quiescent state for any parameter, then the motions are evaluated to determine if there should be a reduction in quiescent state for any parameters.

In order to implement the rule for changing quiescent state from a higher to lower order of precedence (i.e. *red* > *yellow* > *green*), each motion parameter is tracked by a peak-detecting algorithm, which sets a 'peak' flag *true* whenever a positive or negative peak is detected below its limit value. When a parameter changes to a higher state of quiescence (as described above), this peak flag is set to 'false'. The basic logic for changing *motion(i)* from a higher to the next lower state of quiescence is:

IF (*motion(i)* < *limit(i)*) .AND. (*peak(i)* = *true*) THEN *state(i)* = *state(i)* - 1

The actual FDMS evaluation process is somewhat more complex, as each motion parameter has two *red* limit values (a maximum value for positive amplitude and a minimum value for negative amplitude), and similarly, two *yellow* limit values. In many cases, the positive and negative limit values will be the same, but this is not necessary (see Section 6.2). Also, there are actually two peak flags for each motion parameter; one for a peak in the *yellow* 'zone', and another for a peak in the *green* zone. For example, in order to change state from *red* to *yellow*, the current motion must be in either the *yellow* or *green* zone, and its *yellow* peak flag must be *true*. The *true* status for this motions *yellow* flag indicates that a motion peak has been observed in the *yellow* zone more recently than the time at which the state increased from *yellow* to *red* (i.e. when this motion's *yellow* peak flag was set to *false*). In order for the quiescent state to change directly from *red* to *green*, the current motion must be in the *green* zone, and the *green* peak flag must be *true*. Figure 6, described earlier, shows examples of all three possible state reductions: *red* to *yellow*; *yellow* to *green*; and, *red* to *green*. If there is no change in quiescent state for the current data acquisition cycle, then the QPI display bar height is refreshed after all parameters have been evaluated.

The multi-bar ship motions display mode is also keyed to the data acquisition sample rate, but all channels are evaluated to assign bar colour and bar height before refreshing the display.

5.2 Flight planning mode and display

The flight planning mode provides information on ship motion characteristics to assist in decision making for flight planning. An example display for the flight planning mode is shown in Figure 10. It has four main areas: controls are located at the right side of screen (the same as for previous modes); a tabular display of descriptive statistics and operational measures is in the top-central part of the screen; a histogram plot of quiescent period durations in the top-left; and, a multi-panel plot of recent time series data takes up most of the bottom part of the screen. This figure shows a sample of the types of information that can be provided. The actual mix of tabular and graphical data that would be shown on the FDMS flight planning display (or displays) should be determined through consultation with CF personnel, at the time of implementing the FDMS.

5.2.1 Constraints on ship tactics

The flight planning display provides a new source of reliable ship motion information, but in order for the statistics to represent the flying conditions, the ship must maintain the speed and heading for flying stations while the statistics are gathered. If a minimum of 100 wave encounters is used as the criterion for statistical confidence, then from 5 to 20 minutes would normally be required to gather sufficient ship motions data (depending on speed, wave period and heading relative to the waves). In many normal operational situations, this may not be practical, but it might be worth doing in high risk situations such as using the helicopter to rescue people from a sinking vessel in high seas. The flight planning and ship motions display modes could be used together to identify the 'best' speed and heading to take for landing the helicopter, and then the QPI display mode would assist the LSO during the actual landing.

Section 7.5 considers possible future options for combining the FDMS with wave and ship motion models, which would allow the operators to calculate ship motion characteristics for any speed and heading.

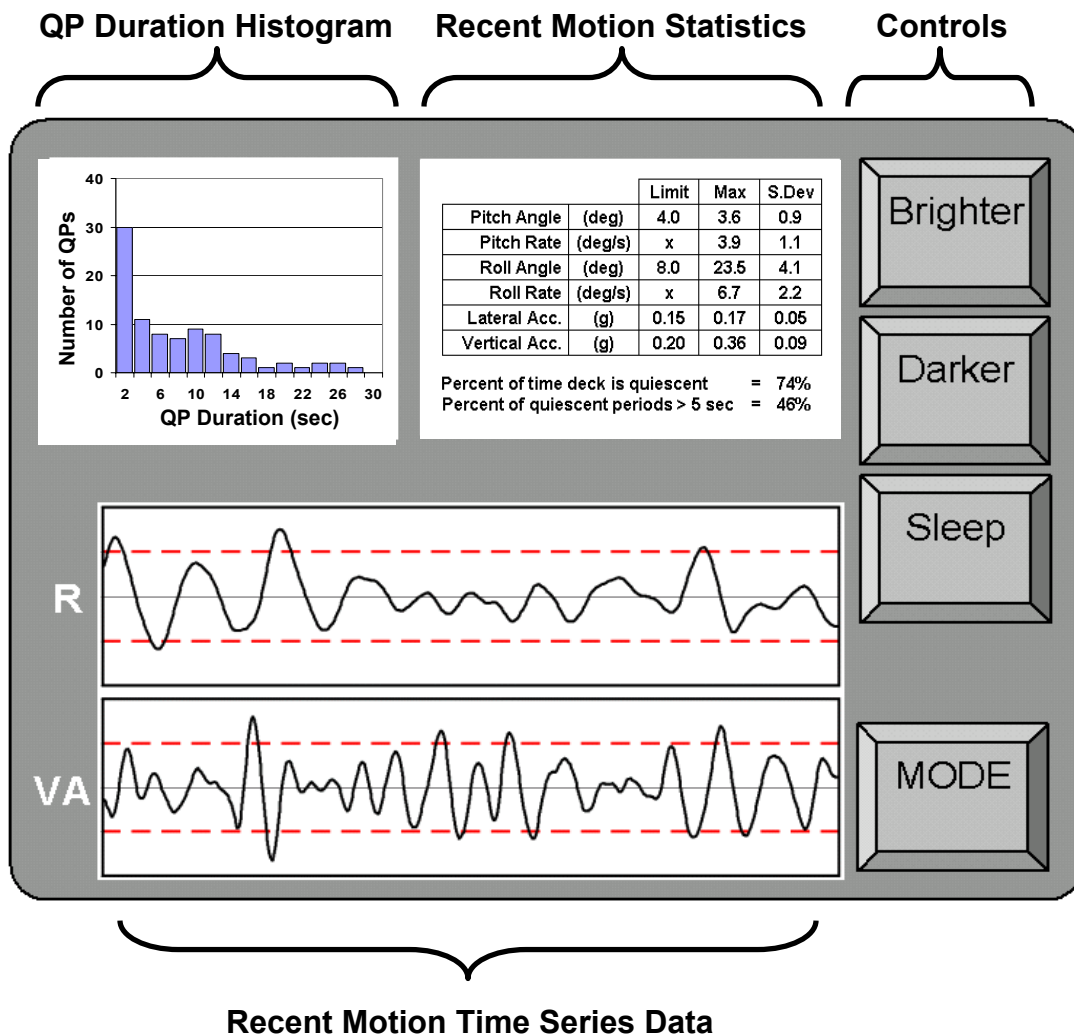


Figure 10: Flight planning display.

5.3 Flight deck data recorder

The flight deck data recorder function is an integral part of the ship motions data acquisition process (described later) that simply stores the measured ship motions to disk on the data processing computer. After every motion sampling sweep is performed and the quiescent period calculations are completed, then the acquired data are stored to disk. Many 'direct memory access' devices allow this to be done effectively in parallel with the calculations.

The flight deck data recorder will use essentially the same display format as shown in Figure 10 for flight planning, with both descriptive statistics and graphical time series data. The playback function requires operator input to define the time interval and motion parameters for display, which will be accessed through system setup commands described in the next section.

The flight deck data recorder requirements for storage capacity are well within the scope of contemporary ‘consumer’ computers. The nine-channel baseline FDMS configuration recommended in Section 6.1 (eight motions and time) requires approximately 5.4 Mbytes of disk storage for each hour of operation. In other words, 1000 hours of continuous FDMS data recording can be held in about 5.2 Gbytes of disk space. For the baseline FDMS, disk space management would be performed as a scheduled maintenance task, not while the FDMS is operating.

5.4 Operator input and system control

Operator input is required to select operating and display modes, and to control a limited number of options, which are described below. As mentioned earlier, the baseline system uses touch-sensitive screens for both display and operator input.

5.4.1 Active command console and visual display switching

The baseline FDMS configuration has two touch-sensitive display screens, one in the howdah and the other in the flight ready room, but only one of them is the *active command console* at any particular time. The switch for selecting which display is the active command console is located in the howdah and controlled by the LSO. This prevents unexpected disruptions in QPI operator guidance for the LSO if somebody touches the display screen in the flight ready room while the helicopter is attempting to land.

The system schematic shown earlier in Figure 7 has different images on the LSO and Ready Room display screens; in practice, both FDMS display screens are ‘slaved’ to the image on the data processing computer, and so the two modes shown in Figure 7 cannot be simultaneously displayed on different screens. For example, if the QPI mode is being used in the howdah by the LSO, then the same QPI display will be shown in the flight ready room.

5.4.2 Basic on-screen controls

The basic on-screen controls shown in Figures 8, 9 and 10 are activated by the virtual buttons on the right hand side of the screen.

The *brighter* and *darker* buttons each make a one-step progression between brighter or darker illumination.

The *sleep* control button shuts the display screen off, but the data acquisition and processing computer continue to run, and any active FDMS modes continue to operate. This allows the operator to ‘wake up’ the system by simply touching any part of the screen.

The *mode* control button cycles the system between the ship motions, QPI and flight planning displays, and also provides access to other support functions, such as invoking the data playback function described above, and a variety of other tasks.

The remainder of this section discusses a few important considerations for the system setup and operating command structure.

5.4.3 System setup and additional controls

A few recommended concepts and features for system setup and control are identified below in point form. Many details cannot be specified until the implementation plan and system technologies are defined.

System startup

- recommended startup configuration is in QPI display mode with the flight deck data recorder turned on
- initial screen brightness should be low to avoid night vision problems.

System control menu (at least one menu-driven screen)

- select criteria set (day or night)
- set flight deck data recorder on/off
- reset statistics gathering for flight planning mode
- select motion channels for display in flight planning and playback modes
- provide virtual numeric keypad to input times for data playback

System shutdown

- when selected from the control menu screen, 'shutdown' will stop active processes, close any open disk files, and put system into *sleep* mode (it will 'wake up' in the default startup mode).
- the motion sensors and data processing computers are physically shutdown using their power switches

6 Ship Motion Parameters and Criteria

This section briefly describes the acquisition and calculation of ship motion parameters, and discusses how ship motion criteria will be implemented for the FDMS. As a general principle, the FDMS will acquire a complete description of the motion environment, but will only evaluate those motions which have reliable criteria.

6.1 Ship motion parameters

6.1.1 Measured motions

The DRDC Atlantic ship motion sensor system [10] establishes the baseline motion measurement capability for the FDMS, which includes the following eight ship motion parameters:

- R roll angle
- RR roll angular velocity (i.e. roll rate)
- P pitch angle
- PR pitch angular velocity (i.e. pitch rate)
- YR yaw angular velocity (i.e. yaw rate = rate of change of ship heading)
- FA longitudinal linear acceleration (i.e. fore and aft)
- LA lateral linear acceleration
- VA..... vertical linear acceleration

The simplified labeling scheme shown in this list reflects the common vernacular used by air crews for naming ship motions, and is consistent with using *FDVA* to define flight deck vertical acceleration [3]. This scheme is also well suited for naming important parameters for likely future consideration, such as vertical velocity (VV), lateral motion (LM), vertical motion (VM), etc..

The FDMS linear accelerations are measured by *strap-down* accelerometers, and so they are *ship-referenced* accelerations, which include the effects of gravity due to ship angular displacement. The ship motion criteria described later are specified in the same ship-referenced coordinate frame. As a consequence, in high sea states, the lateral acceleration includes a significant contribution from gravity, due to large ship roll angles. This is a desirable feature for likely future uses of the FDMS, as ship-referenced lateral acceleration is directly proportional to the lateral forces acting on a mass supported by the flight deck, such as a helicopter secured in the RSD, or a person handling deck equipment.

The FDMS acquires motions as analogue voltage output from the motion sensors, which are filtered with 10 Hz low-pass analogue filters and then sampled at 20 Hz with a 12-bit analogue-to-digital data acquisition system. The ship motion sensor

system is described in detail in [10], and Annex A provides an abbreviated description of sensors, signal conditioning and data acquisition components.

It would be desirable to include ship yaw angle, or heading, in the list of measured parameters, but this is not a simple task for a stand-alone system on a warship, nor is it important for the FDMS to have direct access to yaw angle. Since helicopter operations are performed at nominally constant ship heading and speed, the measured yaw angular velocity channel is a reasonable candidate for possible future motion criteria. An integrated RAST/FDMS control system would have access to ship heading from the ship's inertial navigation system (INS) and/or global positioning system (GPS) information system, but this is not practical for the stand-alone configuration.

It is possible to measure angular accelerations, but these parameters are of relatively low importance, and can be easily calculated if desired, as discussed in the next section. Under special conditions, it is possible to accurately measure linear displacements and velocities using multi-antenna differential GPS, but this requires that the ship remains in close proximity to a stable GPS reference receiver, which is not practical for normal operations.

6.1.2 Calculated motions

The FDMS will have the ability to calculate the following parameters in real time:

- time-based derivatives of any measured motion parameter;
- average roll angle; and,
- linear lateral and vertical flight deck velocities and displacements.

The derivatives of angular velocities and, especially, of linear accelerations (also known as 'jerk') may be of use for defining future motion criteria. Calculating average roll angle will permit assessment of wind-induced heel, which is an important parameter for evaluating asymmetric motion limits, as discussed later. The lateral and vertical displacement of the flight deck describe overall flight deck motion in the 'transverse vertical' plane, which may be of high importance for deriving new criteria. Flight deck velocity is discussed in the next section.

The algorithms for calculating time-based derivatives and averages are simple and fast, but integrating linear accelerations once to obtain velocities and again to obtain displacements is normally a complex and demanding task. This is greatly simplified for the FDMS by assuming that the lateral and vertical linear accelerations, velocities and displacements have zero mean values. This is a good assumption for vertical motion, otherwise the ship is no longer on the surface. This is generally not a good assumption for lateral motions; however, the primary interest is the ship's motions with respect to its nominal straight-line course, and so this assumption is made. Performing accurate integration of longitudinal and lateral accelerations over time is a navigation task performed by the ship's INS,

and not particularly relevant for assessing the effects of ship motion on tasks of relatively short duration.

The selection of which parameters should be calculated, and the definition of algorithm parameters (such as number of points for data smoothing) are system-level options, which are not available to the user during normal system operation.

6.1.3 Relative velocity between ship and helicopter

The relative vertical velocity at touchdown between the helicopter and flight deck is of critical importance for structural integrity of the helicopter's landing gear. In traditional seakeeping design and analysis, limit values are often imposed on flight deck vertical velocity to avoid conditions with high relative touchdown velocity (e.g. [11,12]). This approach implicitly assumes that flight deck vertical velocity is correlated with relative velocity at touchdown, but this is not the case. Detailed analysis of flight deck certification trials data [1] shows that touchdown relative velocity is not well correlated with flight deck vertical motion. This conclusion is substantiated by informal discussions with CF test pilots which indicate that the pilot can land on a deck with high vertical velocity, as long as the pilot is aware of this condition. In order to provide reliable operator guidance on relative velocity between the helicopter and ship, it is necessary to measure the motion of both platforms, as discussed in Section 7.3.

Relative lateral velocity at touchdown is also an important parameter for helicopter tire stability and 'peel-off'. No published data are currently available on correlation between flight deck lateral velocity and relative lateral velocity at touchdown.

6.2 Ship motion criteria

The basic premise for the FDMS is simple: given appropriate ship motion criteria, the system will provide reliable guidance to the LSO on any performance limits related to current ship motions. Thus, it is important to have reliable criteria, which requires that (i) the critical ship motion parameters are selected, and (ii) reasonable limit values are assigned to these parameters. This also implies that arbitrary limits should not be imposed on motion parameters, especially motions which are not critical. This section discusses some important concepts related to ship motion criteria, and describes how criteria will be implemented in the FDMS.

The definition of criteria limit values and selection of which motion parameters are included in the quiescent period evaluation process are system-level options, which are not available to the user during normal system operation. The definition of multiple criteria sets is discussed in Section 7.2.

6.2.1 Real time vs. maximum value criteria

The FDMS requires *real time* ship motion criteria, but existing operational procedures [3,8] use traditional ship/helicopter operating limits (SHOLs), which are *maximum value* criteria. References [1] and [2] discuss the differences between these concepts in some detail, but the major points are summarized here to prevent confusion over this important issue.

Maximum value criteria define conditions in which operations are expected to be possible. For example, on CF frigates and destroyers, ‘hauldown’ landings have typical SHOLs of 20° to 25° for maximum roll angle, and 4° to 6° for maximum pitch angle. These limits represent a statistical description of the ship motion environment in which experience shows that there will be opportunities to land within a reasonable time and with an acceptable margin of safety. These criteria are of use for design studies, equipment specifications and operational flight planning, but they are of little use for providing guidance in real time operations.

Detailed analysis of instrumented ship and helicopter data clearly shows that the actual motions that can be tolerated while the helicopter is at low hover and attempting to land are very much less than the maximum value limits [2]. Ideally, the helicopter maintains relative position over the ship at high hover during large amplitude ship motions, and then descends to low hover and landing when the ship enters a ‘quiescent period’, as described earlier. Real time criteria are defined by the maximum motions that can be safely tolerated at the time of performing an activity. Reference [2] illustrates the development of real time criteria from flight test data for Sea King helicopters operating from City Class frigates in high seas.

6.2.2 Asymmetric criteria

As mentioned earlier, the FDMS will have the ability to evaluate asymmetric criteria, by allowing different limit values for positive and negative limits. This is particularly important for assessing lateral motion effects for two reasons: (i) the ship often has a wind-induced heel angle, in which case the mean ship roll angle is non-zero; and, (ii) the helicopter usually hovers with a non-zero static roll offset induced by tail rotor torque. The Sea King helicopter normally hovers “port-side down”, and so ship roll to starboard is worse than ship roll to port. Asymmetric criteria do not yet exist, but should be considered for future work.

6.3 FDMS criteria

The actual recommended values for preliminary Sea King/City Class real time criteria are not published in this document. The process for deriving these criteria was described in Reference [2], and the values for day time operations are published in the Basic Vehicle Requirements Specification (BVRS) document [13] for the Maritime Helicopter Project (MHP). These criteria were derived from an extensive collection of real operational data, but they have not been validated and so they must be regarded as preliminary criteria. They will provide a starting point for operational testing and evaluation on the City Class, and should provide a good basis for developing real time criteria for the Tribal and AOR classes.

Preliminary *red* limit values are defined for two motion parameters: roll angle and flight deck vertical acceleration; and, for two conditions: day and night. Preliminary *yellow* limit values will be set equal to 0.80 of the corresponding *red* limits, as recommended in [2].

6.3.1 Multiple criteria sets

In order to handle the two criteria sets identified above for day and night operations, and to support development of new criteria for different operations in the future, the FDMS will provide general support for multiple criteria sets. Each criteria set has a unique name, and defines limit values for an arbitrary number of ship motion parameters (i.e. any or all of the motion parameters available within the FDMS). For each motion parameter, there are four limit values: a maximum-positive *red* limit; a minimum-negative *red* limit; a maximum-positive *yellow* limit; and, a minimum-negative *yellow* limit. In many cases the positive and negative limits will have the same magnitudes (i.e. symmetric criteria), but this is not a requirement, and so asymmetric criteria can be used.

The FDMS operator will be able to select and change which criteria set is being used while the system is running. The definition of actual limit values and the selection of ship motion parameters to which they are assigned are system-level options, which are not available to the user during normal system operation.

7 Future Considerations

This section discusses topics for potential future consideration. Some of these topics have been mentioned previously, and others are introduced here.

7.1 Operational testing and evaluation

Operational testing and evaluation will be critical for demonstrating that the FDMS concept has real value, and for validating the preliminary real time criteria. If the stand-alone configuration is pursued in the near-term, then it would be desirable to perform informal, *ad hoc* tests with Sea King helicopters. This will provide improved operator guidance and, as discussed in Section 2.1, expand the 'operational envelope', during the transition period from current operations with Sea Kings to future operations with the new CF maritime helicopters (MH). Future formal testing and evaluation of the MH will be facilitated by using the FDMS flight deck data recorder mode to acquire ship motions data during testing, and as the basis for developing new real time criteria.

In addition to these major considerations, the following specific items should be considered:

- determine the best combinations of display colours and brightness for (i) bright daylight, (ii) reduced or dull daylight, and (iii) night;
- determine the optimum clearance between the limit line and the top of the screen for the quiescent period display modes;
- assess whether the assumption of a zero mean for lateral linear accelerations is acceptable;
- determine if contemporary COTS computers provide adequate real time response for simultaneous evaluation of a realistic combination of measured and calculated motion parameters.

7.2 Application to other operations: new criteria

The FDMS concept of providing real time operator guidance is applicable to a wide variety of motion-sensitive tasks, including both helicopter/ship operations and general shipboard activities. There are two key considerations; (i) defining appropriate criteria, and (ii) providing the information in real time at the location where it is required. This section identifies a number of 'other operations' which are particularly motion-sensitive, and the next section on future enhancements includes a discussion of technologies for portable FDMS displays.

7.2.1 Other flight operations

Section 3.4 lists a number of helicopter/ship operations which are all affected by ship motions to a greater or lesser extent, and which may benefit from FDMS real time operator guidance. All of these activities, with the exception of VERTREP at the bow of the ship, are performed at the flight deck, and so the FDMS howdah display is in a good location for providing operator guidance - the only missing ingredients are appropriate criteria sets.

A few activities which are particularly sensitive to ship motions are listed below; many of these activities are applicable to both the Sea King and MH, but some may not apply to the MH, depending on its actual systems and procedures:

- freedeck landings (i.e. without the hauldown cable);
- any situation with the helicopter on deck but not secured in the RSD;
- any situations with humans moving around on the flight deck, in particular,
 - preparations for a hauldown landing (i) grounding the messenger cable, lowered from the helicopter, and (ii) attaching the hauldown cable to the messenger cable,
 - relaying the fueling hose to the helicopter for HIFR, and
 - for the Sea King: (i) unlatching the tail boom prior to folding it, and (ii) 'walking' the blade tips as the rotor is folded to keep the blade tips from hitting the deck; and,
- any situations with humans handling heavy objects, in particular,
 - moving, loading and unloading torpedoes and (in the future) missiles,
 - sending and receiving personnel and goods for VERTREP, and
 - major maintenance activities, such as replacing engines or gear box.

7.2.2 General shipboard activities

General shipboard activities which are affected by local accelerations (which is virtually all of them), should be evaluated for local accelerations, not for accelerations at the flight deck, where the FDMS motion sensors are located. If the FDMS has the capability to calculate accelerations at arbitrary locations in the ship (as discussed in the next section), then the two key considerations which remain are; (i) defining appropriate criteria, and (ii) providing the information in real time at the location where it is required.

The baseline FDMS configuration with displays in the howdah and pilot ready room can provide some guidance for performing more general shipboard activities, but the utility for real time guidance is reduced unless the activities are being performed near to the displays. This assumes that the person monitoring the FDMS should also be able to watch the activity being performed. Introducing a FDMS display on the bridge would allow real time assessment of motion limits on foredeck activities, especially loading missiles into a Tribal Class vertical launch system (which is normally done in harbour). A bridge or bridge wing

display may also be helpful for guidance on boat launch and recovery, replenishment at sea (RAS) activities, and ‘servicing’ weapons and sensors launching systems, especially for reloading the hangar-top close-in weapon system (CIWS), but this type of guidance would be greatly enhanced by providing a portable FDMS display, as discussed later.

7.3 FDMS enhancements

This section describes a number of possible future enhancements to the FDMS which would increase its applicability and capability.

7.3.1 Portable FDMS display

In order to take best advantage of the FDMS capability, it is desirable to have ready access to the FDMS display. In special circumstances, it may be possible to monitor a remote display and relay warnings or instructions through existing communication systems, but this would be very cumbersome. If an integrated FDMS/RAST control system is developed, then it may be practical to make FDMS quiescent state information available on existing digital ship information systems, for remote access through plug-in display terminals. Contemporary COTS solutions exist for developing portable FDMS displays using wireless networking technologies, but the viability of this approach is subject to constraints imposed by possible interference with ship and weapon systems, and could probably not be used during operational requirements to control electromagnetic emissions from the ship.

7.3.2 Calculate accelerations at any location

It is desirable to have the capability for calculating ship-referenced accelerations at any arbitrary location in the ship; however, this is not recommended for the FDMS baseline configuration, as the initial focus is on helicopter operations, and there are already a relatively large number of new concepts, operating options and potential capability/performance trade-offs to be assessed.

The algorithm for calculating ship-references accelerations at locations remote from the flight deck is a simple transformation, which only requires knowledge of relative positions. Implementing this capability into the FDMS will require introduction of a new feature for defining the location at which an activity is being performed, but this new feature will not change the way criteria sets are defined.

7.3.3 Ship and helicopter information

The utility of the FDMS can be increased by combining information on ship motion with information on ship speed and course. This information is readily available, but could not be easily integrated with a stand-alone configuration. An integrated system could provide this information in a new display mode, based on a wind envelope display (see Figure 1), with current relative wind speed and direction overlaid on the plot. The relative wind information can be calculated from ship speed and course, and wind speed and direction.

A higher level of FDMS performance can be attained by combining the measured ship motions with data on helicopter position, attitude and/or performance. As discussed earlier, information on relative velocity between the helicopter and flight deck near and at the time of touchdown would be of high value, but requires additional information. A limited capability can be readily obtained by recording hauldown cable velocity: this will specify the relative velocity magnitude, but not direction; however, if one assumes that the helicopter is more-or-less positioned over the RSD, then the primary contribution to the relative vertical velocity would be in the vertical direction. Adding this one parameter to the FDMS would greatly increase its utility for both landing the helicopter and documenting the distribution of touchdown velocity (i.e. quantify 'hard' landings).

A number of existing COTS and emerging technologies are available to measure helicopter location and attitude, including differential GPS and laser range finders; however, there must be an active data link between the helicopter and ship in order to combine the two data sets. If a data link was available, then it would also be possible to consider incorporating pilot workload and helicopter performance data, such as control input activity (e.g. stick movement), control margins, engine torque and engine power. These parameters are important for documenting performance limits during flight deck certification trials, and their inclusion with a ship-based data acquisition and evaluation system would allow for better performance monitoring and 'extending the envelope' during fleet operations.

7.3.4 Wave and ship motion models

The final aspect of possible future enhancements mentioned here is to consider integrating the FDMS with existing methods for calculating ship motions (e.g. [4]) and existing or new methods for defining the ocean wave environment, as discussed in [1]. This capability would greatly enhance the flight planning mode by assessing likely ship motions and consequences for helicopter operations at any ship speed or heading, without having to actually measure motions at those conditions.

8 Conclusion

Important concepts and system parameters for a real time operator guidance capability using a Flight Deck Motion System (FDMS) have been described. The focus has been on a simple stand-alone system for assisting with helicopter landings in high sea states, but the basic concepts are applicable to a wide variety of motion-sensitive helicopter/ship and general shipboard activities.

Canadian Forces (CF) operational procedures for landing helicopters in high seas were reviewed, and a methodology for quantifying quiescent periods in real time was described. Recommended FDMS components and locations were identified, and system operating modes are summarized, including displays and processing methods for quiescent period indicators, ship planning information, and a flight deck data recorder. The acquisition and calculation of required ship motion parameters were discussed, procedures for defining suitable motion criteria were described, options for future enhancements were considered.

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Notation

AOR	auxiliary oiler/ replenishment support ship
AETE	Aerospace Engineering Test Establishment
CF.....	Canadian Forces
CIWS	close-in weapon system
COTS	commercial off-the-shelf (i.e. existing products)
CPF	Canadian Patrol Frigate
FDMS.....	Flight Deck Motion System
FA	longitudinal linear acceleration (i.e. fore and aft)
FD	flight deck
FDCR	Flight Deck Control Room (site for FLYCO)
FDCT	flight deck certification trial (trial authority is AETE)
FDVA	flight deck vertical acceleration
FLYCO	flight deck coordinator
GPS	global positioning system
HHRSD	Helicopter Hauldown and Rapid Securing Device (RSD)
HIFR	helicopter in-flight refueling
Howdah	LSO compartment, contains RAST console
INS	inertial navigation system
LA	lateral linear acceleration (ship referenced)
LSO.....	Landing Safety Officer
MHP	Maritime Helicopter Project (i.e. Sea King replacement)
MV	maximum value (e.g. MV criteria)
P	pitch angle
PR	pitch rate (i.e. angular velocity)
QPI	Quiescent Period Indicator
R	roll angle
RR	roll rate (i.e. angular velocity)
RAS	replenishment at sea
RAST	Recovery Assist, Secure and Traverse system, includes RSD, tail-straightening and deck traverse sub-systems.
RMS	root mean square, descriptive statistic
RR	roll angular rate (angular velocity)
RSD	Rapid Securing Device (i.e. beartrap)
S.Dev	standard deviation, descriptive statistic
SHOL	Ship/Helicopter Operating Limits (ship motion criteria)
VA	vertical linear acceleration (ship referenced)
VERTREP	vertical replenishment
YR	yaw rate (i.e. angular velocity)

Annex A Ship motion sensors and data acquisition

A.1 Linear acceleration

sensor type: triaxial, linear force-balance accelerometer
manufacturer: Columbia Research Laboratories, Inc., Woodlyn PA, USA
model: SA-307TX,
accuracy: +/- 0.2% of full scale (F.S.)
axes: longitudinal acceleration, F.S. = +/- 1 g
lateral acceleration, F.S. = +/- 1 g
vertical acceleration, F.S. = +/- 2 g, measures 1 g at rest.

A.2 Angular displacement and rate

sensor type: triaxial angular rate and biaxial angular displacement sensor
manufacturer: Watson Industries, Inc., Eau Claire WI, USA
model: ARS-A2C332-1A
accuracy: +/- 2% of reading, for both attitude and rate.
axes: roll angle, ϕ F.S. = +/- 30°
pitch angle, θ F.S. = +/- 30°
roll angular velocity, F.S. = +/- 10°/sec
pitch angular velocity, F.S. = +/- 10°/sec
yaw angular velocity, F.S. = +/- 10°/sec

Note that x10 analogue gains are used on angular velocity sensor output, to reduce the maximum F.S. from +/- 100°/sec, which is appropriate for aircraft, to +/- 10°/sec F.S.

A.3 Anti-alias filters

filter type: analogue, electronic 4-Pole Butterworth, low-pass
manufacturer: Frequency Devices, Inc., Haverhill MA, USA
model: D74L4B-10.0Hz
corner freq.: 10.0 Hz (-3 dB point)
time delay: 0.06 sec (maximum)

A.4 Data acquisition

type: analogue/digital converter (ADC)
manufacturer: National Instruments Corporation, Austin TX, USA
model: DAQcard 700
resolution: 12-bit ADC, with +/- 10 volts analogue input, provides analogue resolution of ≈ 0.0049 volts (= 20 volts / 4096 bits)
sample rate.: 20.0 Hz per channel, over 16 channels (aggregate rate = 320 Hz)
software: National Instruments LabVIEW, version 5

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The Flight Deck Motion System (FDMS) is an active operator guidance system for assisting the shipboard Landing Safety Officer (LSO) when landing helicopters in high seas. New concepts for identifying and tracking 'quiescent periods' in real time are described, and the FDMS capability and reliability are described. Three operating modes are discussed: a quiescent period indicator for real time guidance, a flight planning mode to assist in decision making, and a flight deck data recorder. The measurement and calculation of ship motion parameters is discussed, and the definition of real time criteria is described.

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ship motion
seakeeping
maritime helicopter
quiescent period
flight deck

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